Vietnam Journal of Agricultural Sciences

ISSN 2588-1299

VJAS 2025; 8(2): 2575-2592
https://doi.org/10.31817/vjas.2025.8.2.13

Effect of Heat Stress on the Health and Performance of Dairy Cattle: A Comprehensive Review

Delower Hossain[1,2*], Sabrina Rahman[2], Umme Kulsum[3], Sabiha Zarin Tasnim Bristi[1,3], Md Robiul Karim[4], Anoar Jamai Masroure[1,5], Maksuda Begum[2] & Md Mahabbat Ali[2]

[1]Department of Veterinary Medicine and Animal Sciences (DIVAS), Università degli Studi di Milano, Lodi 26900, Italy

[2]Faculty of Animal Science and Veterinary Medicine, Sher-e-Bangla Agricultural University (SAU), Dhaka 1207, Bangladesh

[3]Faculty of Veterinary Medicine, Chattogram Veterinary and Animal Sciences University, Chattogram 4225, Bangladesh

[4]Faculty of Veterinary Medicine and Animal Science, Gazipur Agricultural University, Gazipur 1706, Bangladesh

[5]Klareco S.r.l., Palazzo Pignano 26030, Italy

Abstract

Heat stress (HS) is a concerning issue for the health and performance of cattle and is manifested by various behavioral and physiological changes. HS leads to a decrease in dry matter intake, rumen activity, growth performance, and milk yield in animals. Extreme HS for at least three consecutive days increases the risk of death. HS also causes a decline in the ruminal microbiota, pH, and acetate concentration, and an increase in lactate-producing bacteria and the lactate concentration. Reduced feed and water intake lead to a decline in milk production. The milk protein and casein content go down due to insulin resistance and apoptosis of mammary epithelial cells caused by oxidative stress, but urea concentrations become higher. Milk's metabolomes, glycine, proline, isoleucine, and phosphocreatine have been found to decrease, while citrate, acetone, and β-hydroxybutyric acid concentrations evidently increase. Blood cell count, glucose, protein, and IgG concentrations also fall due to HS. Short estrus, impaired follicular development, poor quality oocytes and spermatozoa, a reduced conception rate, and decreased semen quality have become very common. For all of this, the present study demonstrates the various effects of HS on cattle health, production, and reproduction.

Keywords

Heat stress, dairy cattle, production, immunity, reproduction

Received: July 7, 2024
Accepted: June 26, 2025

Correspondence to
Delower Hossain
delowervet@sau.edu.bd

Introduction

The dairy industry is immensely important in global food production and significantly contributes to nutritional security and economic development worldwide. Nevertheless, this sector faces significant challenges from environmental stressors, and heat stress (HS) has become a major challenge. HS happens when environmental conditions surpass the thermoneutral zone of dairy cattle, thus hindering their thermal balance (Hossain *et al.*, 2023). The phenomenon is not new, especially in such tropical areas where high ambient temperatures and humidity have been a challenge for livestock producers for a long time. Even in the absence of the impacts of global warming, HS is still a critical concern, particularly in the tropics. The issue is particularly severe for temperate breeds of cattle introduced into tropical regions, as these animals are known to be less able to tolerate high heat loads (Cartwright *et al.*, 2023; Nzeyimana *et al.*, 2023).

Nonetheless, HS has been intensified by global climate change with increasing temperatures and more frequent heatwaves in temperate and tropical regions worldwide. These increased occurrences have globalized the issue, making HS-prone areas places of concern in the dairy industry. Of all livestock species, dairy cattle are particularly susceptible to HS, most notably high-producing breeds such as Holstein-Friesians, predominantly due to a combination of high metabolic heat production and a limited ability to dissipate excess heat (Cartwright *et al.*, 2023; Stefanska *et al.*, 2024). HS not only causes discomfort in cattle but also has significant effects on cattle health, productivity, and fertility. HS has been demonstrated to diminish milk yield, disrupt milk composition, and elevate somatic cell counts, all of which negatively affect milk quality and therefore the quality of consumption (Liu *et al.*, 2019; Cartwright *et al.*, 2023).

High ambient temperatures stimulate a series of physiological and metabolic alterations in dairy cows to deal with HSs. These alterations can involve increased respiration rates, reduced feed intake, altered endocrine function, and oxidative stress, disturbing normal biological processes (Cartwright *et al.*, 2023; Nzeyimana *et al.*, 2023). HS at the cellular level activates the expression of heat shock proteins (HSPs) that play a significant role in preventing damage to cells. At the same time, the energy needed for this protective response takes away from productive functions like milk synthesis and reproduction, leading to measured performance declines (Wolfenson & Roth, 2019; Stefanska *et al.*, 2024). In addition to production loss, HS impairs the immune system and increases susceptibility to diseases (e.g., mastitis) and metabolic disorders (e.g., acidosis) (Roth, 2020; Singha *et al.*, 2021; Cartwright *et al.*, 2023).

The economic burden HS poses on the dairy industry is significant. Dairy farmers face substantial economic losses due to decreased milk production, poor fertility, increased health problems, and greater mortality rates. Annual estimates in lactating cows show HS contributes a USD 1.5 billion loss in productivity due to decreased production (Roth, 2020; Stefanska *et al.*, 2024). These losses are exacerbated by the additional costs of implementing abatement strategies, including cooling systems and dietary changes (Liu *et al.*, 2019; Nzeyimana *et al.*, 2023).

Given the growing global demand for dairy products and the intensifying effects of climate change, understanding and mitigating the impacts of HS on dairy cattle is more critical than ever. This comprehensive review aimed to compile and consolidate data on HS and its effects on dairy cattle health, performance, and fertility. By providing a thorough synthesis of the current research on this topic, this review sought to offer insights into the physiological mechanisms underlying HS responses and their practical implications for dairy management. Through this consolidation of knowledge, we aimed to inform researchers and practitioners about effective approaches to safeguard dairy cattle health and performance in a warming world.

Indicators of Heat Stress Level

Cattle are sensitive to HS, particularly those fed high amounts of feed for milk production, which raises the body temperature due to a fast metabolism. When the temperature and humidity rise, cows may begin to feel HS. There are two primary indicators of HS in cattle, physiological and behavioural (Hoffmann *et al.*, 2020). The major physiological signs include changes in respiration, heart rate, panting, temperature, and milk yield, while behavioural indicators include searching for cool places, laying patterns, rumination frequency, and feed and water intake. While under extreme HS, cows typically pant and breathe through their extended necks. However, it is challenging to compare different barn locations, housing, breeds, ages, and milk production of cows, and various thermal indices and formulas have been used to calculate them. Accurately recording respiratory signs requires considerable effort and time. Moreover, cortisol metabolite analysis is expensive and technically advanced (Idris *et al.*, 2021). The level of HS along with their effects on dairy cattle is presented in **Table 1**.

Effects of Heat Stress on the Health of Dairy Cow

Water intake

Water is the prime priority in order to maintain one's body fluid concentration during periods of elevated temperatures. HS increases the water requirements to rehydrate the body and replenish water lost by excessive sweating. Providing insufficient water to dairy cattle can hamper milk production, growth, metabolism, and health. For each pound of milk production, lactating dairy cows require 4.5-5 gallons of water (Looper & Waldner, 2002; Gorniak *et al.*, 2014). A slight reduction in water intake reduces DMI by 1-2 lbs per day, which can reduce milk output by 2-5 lbs. Water requirements may increase from 21 to 32 gallons when temperatures rise from 86 to 95°F. High-milk-producing cows are more susceptible to HS compared to less-producing cows because of their increased heat emissions, higher feed consumption, and greater water requirements for maintaining hydration (Collier *et al.*, 2014).

Growth performance

Exposure to high temperatures leads to a deterioration in growth performance in cattle. Both total weight gain and average daily gain are notably lower in the summer compared to the winter season. HS negatively impacts the growth performance of heifers and calves as well (Wang *et al.*, 2020; Hossain *et al.*, 2023). HS in dairy cows results in decreased DMI, metabolic rates, and vasodilation behavioral changes, leading to blood hormone concentrations and body temperature alterations, ultimately impacting growth performance.

Physiological impact

Dairy calves regulate their thermal energy balance to maintain a consistent body temperature during HS. To maintain a thermal energy balance, their metabolism (endeavor, restoration, development, lactation, gestation, and DMI) must generate as much convective heat as energy lost to the atmosphere. Thermal balance cannot be maintained when an animal cannot sufficiently release metabolism-generated or absorbed heat. Thus, the physiology and behavior of animals are both impacted by HS, which can be detrimental to animal welfare. Many physiological and behavioral reactions assist in regulating body temperature under HS, but both are affected by weather, and alterations are more noticeable when an animal lacks shelter (Schütz *et al.*, 2010; Hossain *et al.*, 2023). Cows spend less time sleeping and more time in the shade or near the water basin as HS rises.

Dry matter intake and rumen physiology

HS poses significant challenges for dairy farmers in milk production. There are common patterns observed in rectal temperature, milk production, and DMI. Rectal temperature rises in cows within 24 hours following HS; consequently, milk yield and DMI decrease after 48 hours (Wheelock *et al.*, 2010). HS triggers the activation of the hypothalamus center for appetite suppression, leading to a reduction in DMI. During hot weather, DMI can decrease by 10-30% or more (Wheelock *et al.*, 2010; Das *et al.*, 2016). In lactating cows, the decline in DMI begins at ambient temperatures of 25-26°C, and in temperate climates, it further accelerates beyond 30°C, potentially resulting in a decrease of approximately 40% at 40°C (Rhoads *et al.*, 2013). A cow usually stops eating when the temperature reaches above 68°F. Every degree above 68°F reduces DMI by 0.17 lbs. For every pound of reduced DMI, milk production drops by 2 lbs (Gorniak *et al.*, 2014).

The most salient pH buffer for the rumen and reticulum is saliva. The act of chewing encourages salivation and aids in digestion. Based on how much time is spent chewing grain,

Table 1. Heat-related indicators in cows under different levels of heat stress and the temperature humidity index (THI) (Kim *et al.*, 2022; Rodriguez-Venegas *et al.*, 2023)

Level of HS	THI	Body temperature (°F)	Respiration rate (BPM)	Heart rate (BPM)	DMI (kg)	FCE (units)	Lying Time (h)	Standing time (h)	Milk yield loss (lbs\cow\day)	Water intake (gallons /day)	Other indicators
No HS	Less than 68	101.5-102.5	40-60	48-60	23.58 ± 0.19	1.575 ± 0.01	10.71 ± 0.15	-	Normal	-	-None -Optimum productive and reproductive performance
Mild	68-71	102.5-103	60-75	62.75	23.77 ± 0.90	1.562 ± 0.01	10.53 ± 0.07	5.49	>2.5 lbs	12.13	-Cows seek out shade -Dilation of blood vessels
Mild to moderate	72-79	103-104	75-85	65.75	22.76 ± 0.05	1.558 ± 0.003	9.46 ± 0.04	6.24	>6 lbs	-	-Increased saliva secretion -Reproductive performance is severely affected
Moderate to severe	80-90	104-105	85-100	72.13	21.59 ± 0.80	1.514 ± 0.005	8.52 ± 0.06	6.61	>9 lbs	16.69	-Excessive saliva production -Significantly decreased reproductive performance
Severe	90-99	Over 105	100-104	-	-	-	-	-	>10 lbs	-	-Cows may die

Note: THI: temperature humidity index, BPM: breaths per minute/ beats per minute, FCE: feed conversion efficiency

FCE is estimated by calculating the kilograms of milk produced by a cow in relation to the kilograms of dry matter intake (DMI)* an adult cow produces about 50 quarts of saliva daily (Jane *et al*., 2017). Saliva accompanies enzymes for the breakdown of fat (lipase) and starch (amylase), and aids chewing and swallowing. It is also involved in recycling nitrogen from the rumen. Saliva production is limited when the rumen mat is not properly structured. During HS, there is a decrease in ruminal acetate and pH levels, while the concentration of ruminal lactate is elevated, and the rumen microbiota is altered. Heat-stressed cows produce significant amounts of soluble carbohydrates, such as those produced by *Ruminobacter* spp. and *Treponema* spp., along with lactate-producing bacteria like *Streptococcus* spp. and unclassified Enterobacteriaceae (Kim *et al*., 2022). HS reduces rumination, rumen activity, reticulo-rumen motility, and rumen pH in dairy cows but increases lactate production (Zhao *et al*., 2019). It is well documented that HS modifies rumen functions by elevating the synthesis of propionate and butyrate, and dwindling acetate concentrations. The fractional digesta passage rate in the gastrointestinal tract is slower in animals perceiving HS, pointing to a reduction in rumen motility and DMI (Figure 1)**.

Acid-base equilibrium

HS occurs when the regulation mechanisms of the body to control and regulate both internal and external temperatures are impaired. In dairy cattle experiencing HS, increased sweating and rapid breathing result in higher fluid loss from the body. HS is also crucial for maintaining blood homeostasis and hydration. Heat-stressed cows exhibit an altered acid-base balance compared to cows with a normal body temperature. Within a narrow range, the acid-base state is carefully regulated in dairy cows (Afzaal *et al*., 2004). This delicate balance of physiological functions involves various mechanisms within cells, blood, lungs, and kidneys, as explained in **Figure 2**. The **Figure 2** illustrates that HS promotes respiration, which excretes more CO_2 than cells produce. Increased CO_2 reduction lowers H^+ and H_2CO_3 levels. However, rising blood pH leads to an increased $HCO3^-$ concentration and respiratory alkalosis. To maintain a higher blood pH, animals excrete $HCO3^-$ and retain H^+ through the urinary

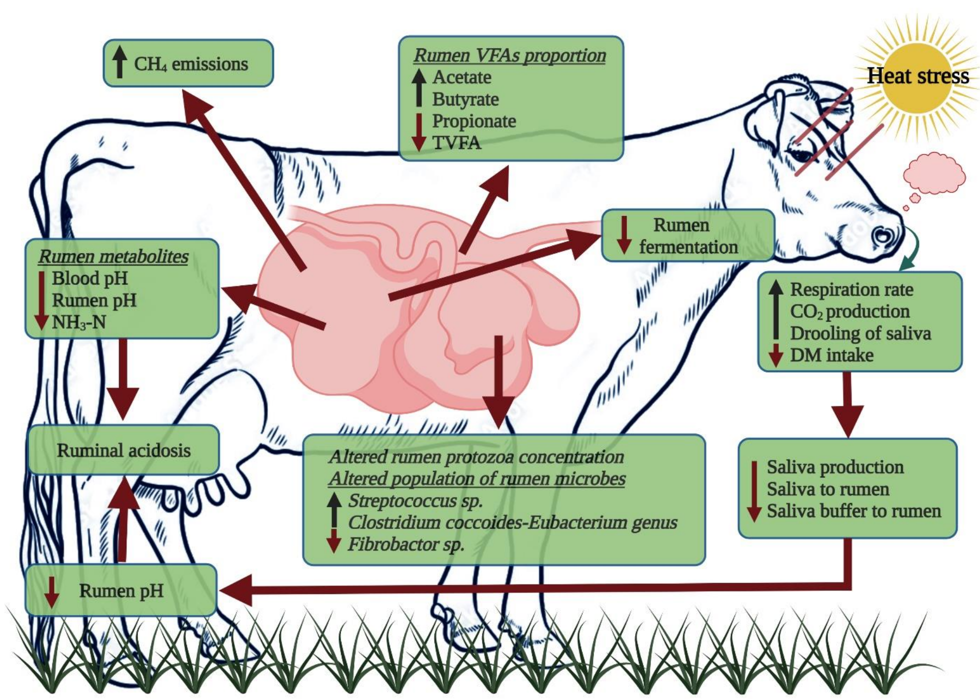

Figure 1. Effects of HS on different rumen functions in livestock animals. VFA: volatile fatty acid; TVFA: total volatile fatty acid; CH_4: methane; NH_3-N: ammonia. The figure was adopted and modified from Rakib *et al*. (2020) and Hossain *et al*. (2023), created with BioRender.com.

system. Retained H^+ maintains the blood H_2CO_3 concentration and forms the blood buffer NH4+. Heat-stressed animals limit their metabolism to reduce CO_2 generation and restore the blood acid-base balance.

Oxidative stress

Under HS, an excess of mitochondrial dysfunction and reactive oxygen species (ROS) causes oxidative stress (OS) in dairy animals (**Figure 3**). The imbalance of oxidant and antioxidant levels is referred to as OS. The cells suffer from oxidative damage because of an excess of oxidants. Dairy calves under HS may incur OS, which is marked by elevated amounts of free radicals in many cells and tissues and hinders body metabolism and typical physiology. ROS are considered the predominant mode by which HS triggers OS and revises milk protein synthesis. Because they decrease mammary epithelial cells, aggravate apoptosis, and affect the endocrine system (Guo *et al.*, 2021). OS fosters insulin resistance and apoptosis, which are negatively linked to the biosynthesis of milk proteins. OS is induced by HS and leads to a reduction in milk protein concentration. This is a tried-and-true tactic that works in some contexts. The consequences of HS-induced OS on milk protein diminution may make it easier to devise novel techniques to lessen the deleterious effects of high air temperatures on dairy cows' inability to produce enough milk in these conditions.

Immune system

Livestock with HS have several health difficulties and an increased risk of impaired immunological responses. A broad network of biological mechanisms protects the body from infection. HS helps release cortisol, which suppresses the expression of genes necessary for T-cell activation and cytokine synthesis, reducing cellular immune responses. Stressors impair immune functions and increase disease risk. In dairy cows, HS activates signal transduction pathways that transform immune cell mediator gene expression, promoting heat shock response and cytokine activity (**Figure 4**). Red blood cells, white blood cells, hemoglobin, the packed cell volume, glucose, and the protein concentration in the blood are the key immune-related markers altered with HS (Das *et al.*, 2016). HS increases the somatic cell count (SCC) in milk but decreases IgG and inflammatory cytokines, affecting lactation (Dahl *et al.*, 2020).

Vaccination is essential for antigen-specific immunity, but HS can affect vaccinated animals by reducing their antibodies or impairing their immune response (Adulkasem *et al.*, 2020). Even after the administration of vaccines, optimal immune reactions may not be enhanced under HS.

Mortality in dairy cows

Prolonged exposure to heat wave-induced HS can lead to increased mortality in dairy cows. When dairy cows are exposed to 32°C for at least three consecutive days, their chance of dying increases (Vitali *et al.*, 2015). Studies have shown that heat waves increase mortality by 27%, resulting in 26 deaths in southern Canada per heat wave (Bishop-Williams *et al.*, 2015).

Effects of heat stress on dairy cow production

Milk production

HS has detrimental effects on the milk yield of dairy animals. A decline in milk production was recorded when temperatures reached 25°C, but a more significant decrease was noticed above 28°C (St-Pierre *et al.*, 2003). Cows with a temperature humidity index (THI) above 68 had a 10-35% drop in milk production in comparison to cows kept in thermoneutral environments (Rensis and Scaramuzzi, 2003; Collier *et al.*, 2006; Wheelock *et al.*, 2010), and at extreme levels, milk production might drop up to 50% (Becker *et al.*, 2020). Every 1°C rise in temperature over the threshold of 21°C resulted in a decrease in milk yield of approximately 0.3-0.5kg milk per day (Marai *et al.*, 2007; Collier *et al.*, 2012). Similarly, several studies found that milk production dropped by 0.05-4kg per day per cow for every unit rise in THI over 72, but these losses are estimated to rise from 1.5-6.5kg by 2050 and 2-7.2kg by 2070 (Sejian *et al.*, 2012; Bernabucci *et al.*, 2014; Ranjitkar *et al.*, 2020). On the other hand, several studies experienced 10-35% more milk production (about 1.02 kg/cow/day) from cows kept in THI lower than

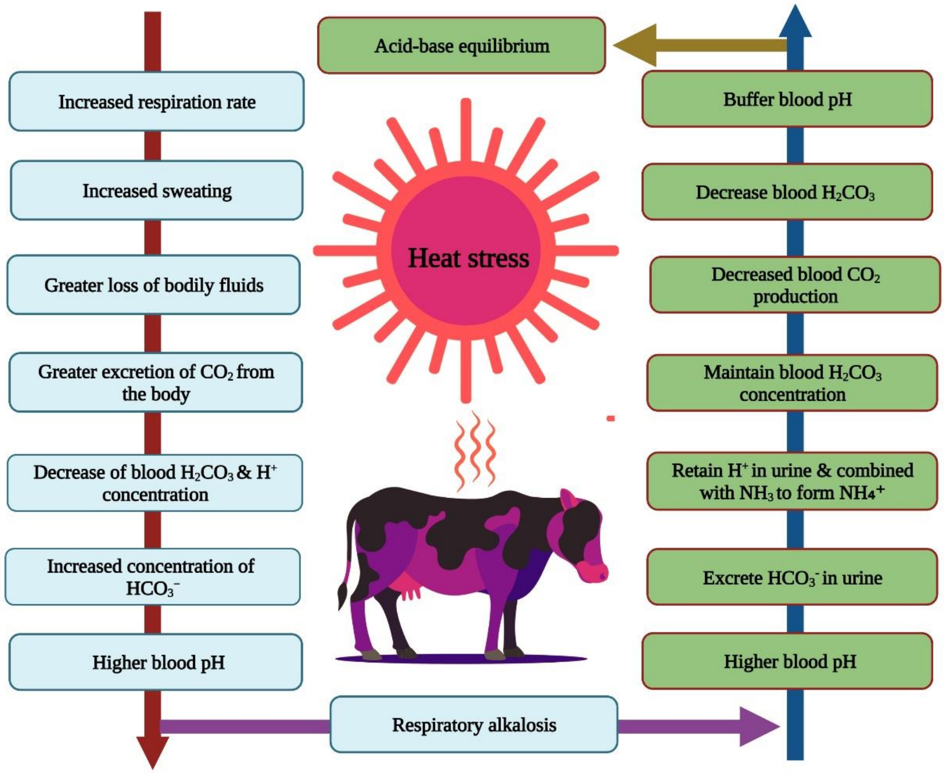

Figure 2. Effect of HS on the acid-base equilibrium in dairy animals (Created with BioRender.com)

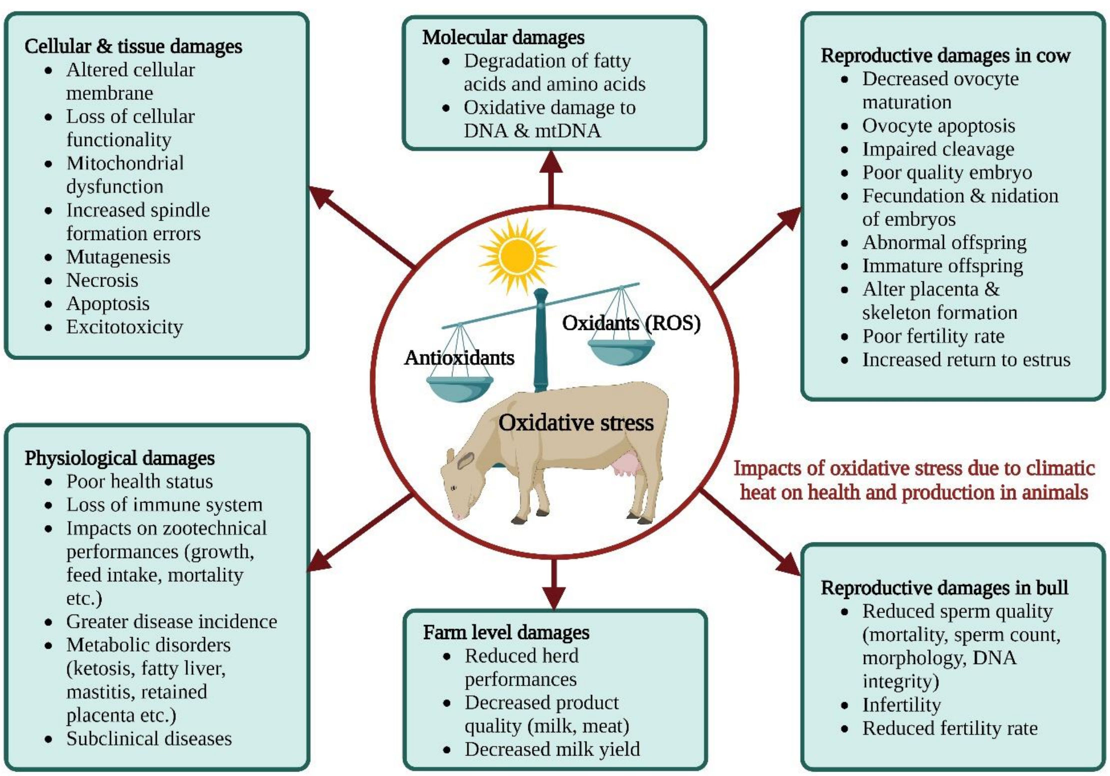

Figure 3. Influences of OS on health and reproduction in cattle due to HS (Created with BioRender.com)

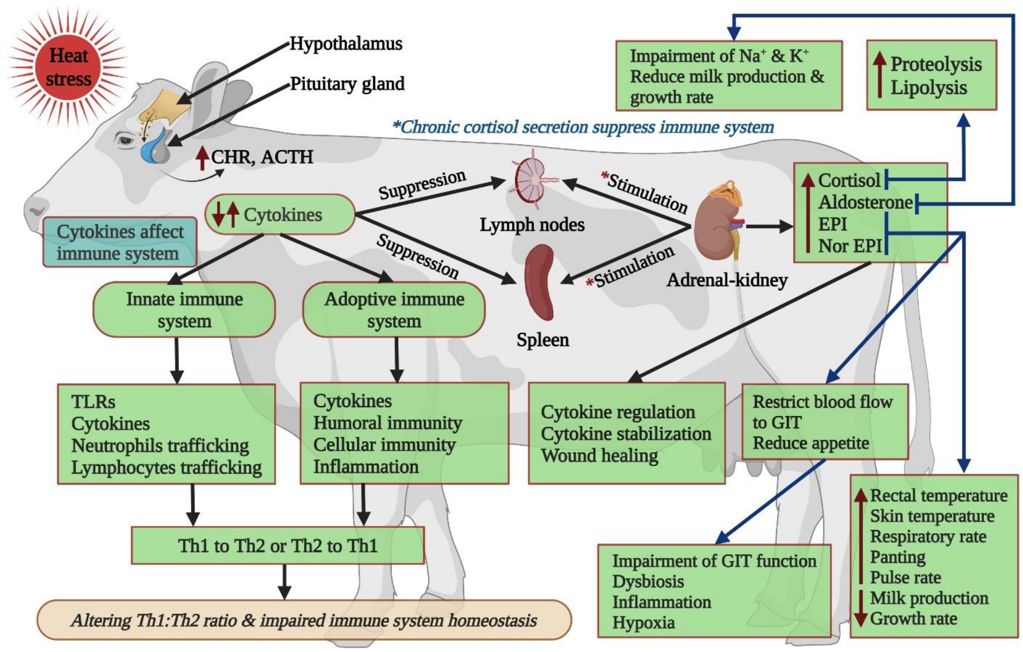

Figure 4. Adverse effects of HS on the immunological functions of animals. ACTH: adrenocorticotropic hormone; CRH: corticotropin-releasing hormone; TLRs: toll-like receptors; Th1: T helper cell 1; Th2: T helper cell 2; EPI: epinephrine. The figure was adopted and modified from Bagath *et al*. (2019) and Hossain *et al*. (2023), created with BioRender.com.

68 (Wheelock *et al.*, 2010; Bernabucci *et al.*, 2014; Dahl *et al.*, 2020). Approximately 50% of the milk yield reducutions in cows during HS was recorded due to reduced DMI, and the rest could be related to metabolic response. Furthermore, mammary cell proliferation during the dry period, lactation period, and calving interval were also affected by HS, and milk production was reduced by the subsequent lactation (Singh *et al*., 2013; Tao & Dahl, 2013). Total annual milk production loss due to HS in India was 3.2 million tons in 2020, which is expected to increase to 15 million tons by 2050 (Das *et al.*, 2016).

Milk composition

The direct influence of HS on cows appears in their milk production capacity and quality. The consequences of HS on dairy cows can be categorized into two distinct aspects: direct and indirect metabolic-physiological effects resulting from reduced DMI. When humidity is low and HS develops, milk yield, composition, and DMI decrease (Peana *et al.*, 2007). Beyond the effects of dietary hindrance, HS decreases milk casein and protein concentrations and skyrockets urea concentrations in milk. Fat, lactose, ash, total solids, and SNF percentages in milk also decrease over time as ambient and core body temperatures rise (Al Reyad *et al.*, 2016). HS has been linked to a rise in αS1-casein and a decrease in αS2-casein. The suppression of mammary protein biosynthesis appears to cause these effects on milk fat and lactose concentrations, not HS (Cowley *et al.*, 2015).

Milk metabolome

Milk biomarkers play a crucial role in identifying the metabolites present in milk and milk-related products, enabling the assessment of their quality and safety. Metabolomics, a recent approach, has been employed to understand the authenticity and nutritional value of milk and its derivatives. Extensive research has identified approximately 223 metabolites in cow milk, encompassing amino acids, lipids, sugars, nucleotides, energy-related compounds, vitamins, co-factors, and short peptides (Sen *et al.*, 2021). HS significantly impacts milk metabolomics. In comparison to the HS-free group, the levels of glycine, proline, isoleucine, and phosphocreatine, which are metabolites associated with proteins or amino acids, were altered in the HS group. It was observed that the concentrations of glycine, proline, isoleucine, and phosphocreatine in the HS group were lower than those in the HS-free group. Furthermore, the citrate concentration in milk was higher in the HS group than in the HS-free group. Additionally, acetone and β-hydroxybutyric acid concentrations were significantly elevated in the HS group compared to the HS-free group (Tian *et al.*, 2016). The upregulation of galactose-1-phosphate in milk may be attributed to heat-stressed dairy cows experiencing a state of negative energy balance.

Effects of heat stress on dairy cow reproductive performance

Estrous cycle and follicular growth

HS impairs reproductive physiology and behavior in dairy cows (**Figure 5**). Cattle spend more time lying down in the summer, and this behavioral shift makes detecting estrus more difficult (Young *et al.*, 2020). HS shortens and escalates estrus, impairs follicular development, and shifts the supremacy of the first-wave dominant and pre-ovulatory follicles in dairy cows. HS halts follicle selection, lengthens the follicular wave, and may profoundly affect oocyte quality (Rensis & Scaramuzzi, 2003). Weeks before ovulation, HS destabilizes the reproductive system by jeopardizing oogenesis and follicular function. Depending on the animal's metabolic status and whether the HS is temporary or prolonged, plasma levels of progesterone can rise or fall. These endocrine tweaks lower follicular activity and thwart the ovulatory process, which lowers the quality of the oocyte and embryo. Due to HS, follicular dominance is mitigated in cows, resulting in an increase in big follicles on the ovary, higher circulating levels of follicle stimulating hormone, and lower levels of estradiol 17β and inhibin. Since follicular dominance is eroded with HS, upwards of one dominant follicle can sprout, and this may increase the summertime twinning that is often noted. HS can assist in reducing follicular steroid discharge and increase the twinning rate, boosting the number of dominant follicles throughout a follicular wave and recurrent ovulations near the culmination of the estrous cycle (Young *et al.*, 2020).

Fertility

The increased body temperature caused by HS leads to a significant reduction in fertility and reproductive capabilities, making it difficult for cows to conceive. HS affects various aspects of reproductive physiology and lowers conception rates in dairy cows globally (Wolfenson & Roth, 2019). The reduced ability of lactating cows to regulate their body temperature during the summer is attributed to decreased thermoregulatory competence, which is linked to lower reproductive success, primarily due to the intensive genetic selection for high milk production. Hormonal treatments, such as eliminating old follicles developed under HS, modifying blood progesterone levels after insemination, and administering GnRH during insemination, have been suggested by Flamenbaum & Galon (2010) to improve oocyte quality. Furthermore, poor fertility can also be observed following artificial insemination under HS.

Embryonic growth and development

HS significantly hinders fetal development and leads to early-stage pregnancy loss in cows. The critical period of expansion and growth during embryonic development poses a major challenge for the dairy industry. HS negatively affects embryonic survival by impeding the warming process during ovulation, thereby reducing embryo viability (Hansen, 2019). The drop in embryonic survival caused by HS can have detrimental effects on growing zygotes and embryos. At day 17, a crucial stage in embryonic development, heat-stressed embryos exhibit slower development and remain underdeveloped (Young *et al.*, 2020). HS interferes with key fertility events necessary for embryogenesis, such as suppressing estrus activity, altering follicular development, reducing oocyte competence, and impeding embryonic development. The first seven days of embryogenesis are particularly susceptible to the damaging effects of HS. While embryos at the 16-cell stage are less prone to HS, those at the 2-cell stage are highly sensitive. As the embryo progresses to the blastocyst stage, it becomes more resilient to HS, particularly during later phases like the morula stage (Hansen, 2019).

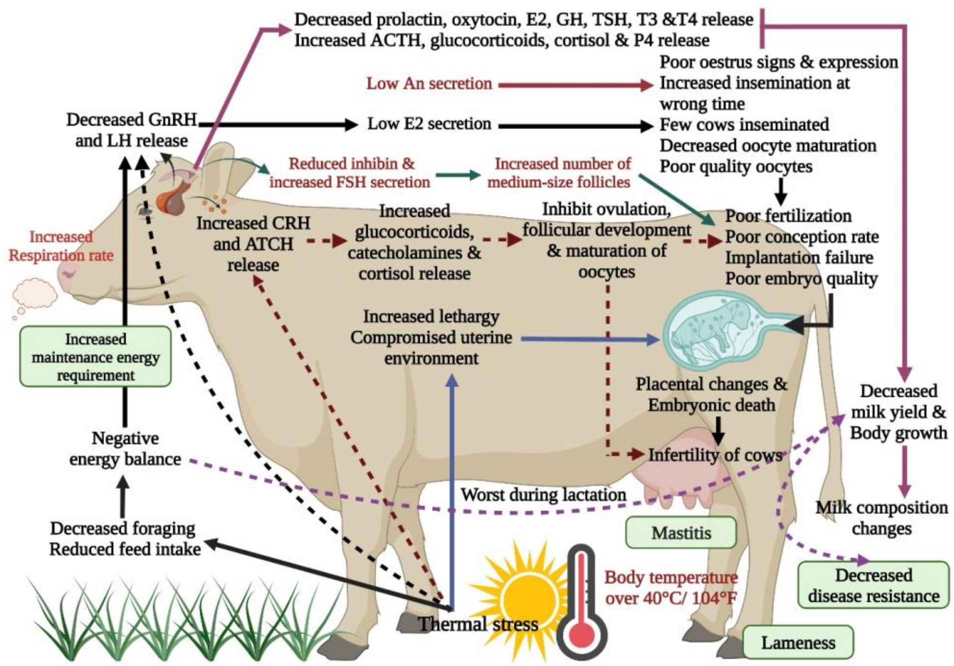

Figure 5. Effects of HS on reproduction, milk yield, and the hormonal balance of cows. GnRH: gonadotropin-releasing hormone; ACTH: adrenocorticotropic hormone; CRH: corticotrophin-releasing hormone; LH: luteinizing hormone; TSH: thyroid-stimulating hormone; T3: triiodothyronine; T4: thyroxine; GH: growth hormone; E2: estradiol; P4: progesterone; An: androstenedione; FSH: follicle stimulating hormone. The figure was adopted and modified from Krishnan *et al*. (2017) and Hossain *et al*. (2023), created with BioRender.com.

HS is associated with embryonic death within the first six days of development, as the rising internal temperature of cows (above 39°C) leads to a lack of thermal proteins that protect the embryo in the uterus. This results in compromised blastocyst formation, reduced implantation, and increased embryonic lethality, ultimately leading to diminished reproductive success in cows (Naranjo-Gómez *et al.*, 2021).

Effects of HS on the reproductive system of breeding bulls

Dairy production and reproduction entirely rely on bull genetics and reproductive performance. Maintaining a temperature difference of 4-5°C between the testicle and rectal temperatures is crucial for efficient sperm production in bulls. However, HS significantly affects sperm quality by impacting a bull's ability to produce viable sperm at temperatures above 15-20°C (Krishnan *et al.*, 2017). High ambient temperatures, humidity, solar radiation, and a lack of wind pose risks to male reproductive fitness, leading to a decrease in both sperm count and quality. High temperatures interfere with the aerobic metabolism of glucose in sperm cells, resulting in mitochondrial dysfunction, accumulation of ROS, increased lipid peroxidation, and a higher occurrence of sperm deformities. HS can alter a bull's endocrine system, leading to changes in sperm morphology, testicular atrophy, and a reduced healthy and viable sperm count. If bulls are exposed to high temperatures, the seminal fluid volume decreases during the initial six weeks of HS, and the percentage of motile sperm decreases after two weeks of HS. Heat-stressed bulls experience elevated cortisol levels and reduced testosterone levels. While cortisol helps the animal cope with high environmental temperatures, it has been found to decrease testosterone production, which is crucial for sperm production and sexual activity. Testosterone reduction impacts reproduction. At high temperatures, testicular metabolism increases, doubling the need for oxygen to sustain aerobic metabolism. HS impairs spermatogenesis, reduces the concentration of sperm with motility, and increases the proportion of malformed sperm, leading to poor rates of implantation, embryonic development, and ultimately subfertility or fertility problems (**Figure 6**) (Capela *et al.*, 2022).

Effects of HS on diseases in animals

HS has a negative impact on the extent, severity, and timing of epidemics of animal diseases. The effects of HS on animal health and well-being are multifaceted, involving changes in ambient temperature, humidity, and the intensity of extreme weather events. High temperatures and increased relative humidity create favorable conditions for the accelerated growth of infectious agents and parasites (Takken & Koenraadt, 2013; Wint *et al.*, 2018; Jánová, 2019). Vector-borne diseases, including protozoal and parasitic diseases (ehrlichiosis, trypanosomiasis, babesiosis, theileriosis, cowdriosis, fascioliasis), rickettsial diseases (anaplasmosis), viral diseases (lumpy skin disease, Crimean-Congo hemorrhagic fever, rift valley fever, bluetongue, Japanese encephalitis, bovine ephemeral fever), and bacterial diseases (pinkeye, coxiellosis, dermatophilosis, anthrax, leptospirosis) in different livestock animals are particularly affected by changes in precipitation and heat load, influencing disease transmission (Takken & Koenraadt, 2013; Wint *et al.*, 2018). Changes in precipitation patterns and temperature can facilitate the transmission of disease vectors and microparasites as well as the introduction of new diseases in livestock. High ambient temperatures enhance the activity of disease-carrying arthropod vectors and increase the likelihood of infection transmission between hosts (Takken & Koenraadt, 2013; Wint *et al.*, 2018; Jánová, 2019). A summary of heat-sensitive livestock diseases is tabulated in **Table 2**.

Effects of HS on Intramammary Infections

The phagocytic functions of polymorphonuclear (PMN) cells are altered by high ambient temperatures (41°C for 2 hours).

Environmental temperature also interferes with the oxidative burst of these PMN cells (Lecchi *et al.*, 2016). HS has a damaging effect on udder health by diminishing the immunological function of both lactating and dry cows. In addition, the expression of miRNA and

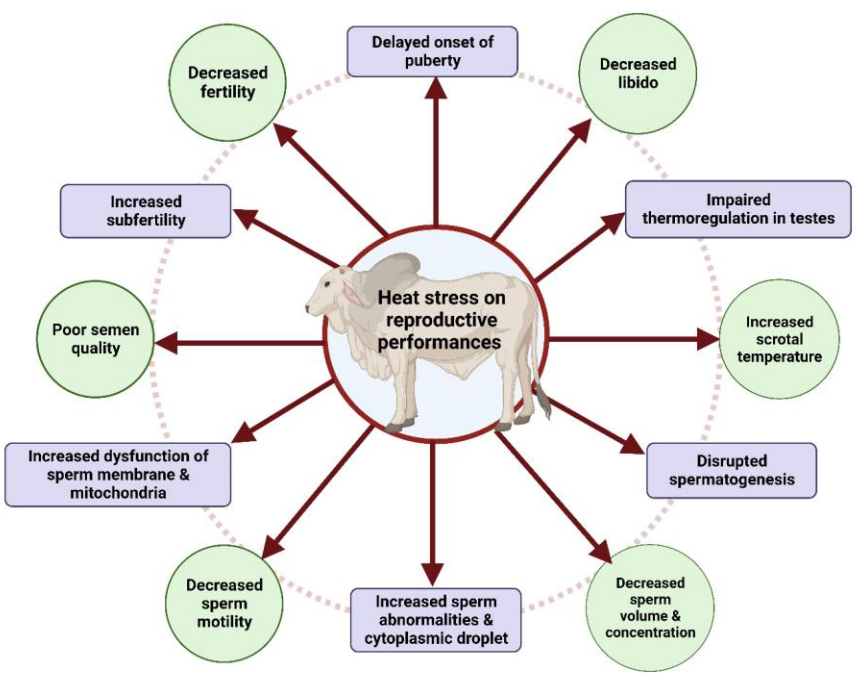

Figure 6. Effects of HS on the reproduction system in bulls (Created with BioRender.com)

apoptotic genes is disrupted, which lowers immunity. Immunosuppression can persist for an extended duration during the entire production span of dairy cows and can negatively affect the response of animals to various infectious agents (Riekerink *et al.*, 2007; Alhussien *et al.*, 2016; Dahl *et al.*, 2020; Rakib *et al.*, 2020). Cattle with a lower immune system are more vulnerable to mastitis and other intramammary diseases. Consequently, the prevalence of mastitis is common in cows with a high THI (Riekerink *et al.*, 2007; Alhussien *et al.*, 2016; Rakib *et al.*, 2020). Individual SCC and bulk milk SCC also rise during the summer season (Lievaart *et al.*, 2007). According to Shock *et al*. (2015), 50% of herds with an increased bulk milk SCC were measured in the hot and humid months. In another study in the USA, Ferreira & De Vries (2015) found greater bulk tank SCC in milk from hot and humid areas than cooler areas. Furthermore many bacterial pathogens that might infect mammary glands thrive in hot environments. *Escherichia coli* and *Klebsiella* spp. are the most frequently isolated environmental pathogens from clinical mastitis in the summer season (Gao *et al.*, 2017). The rate of udder infections was found to be considerably higher by *Streptococcus (S.) dysgalactiae* and *S. uberis* in thermally stressed dairy cows with a decreased number of viable epithelial cells (Almeida *et al.*, 2018; Dahl, 2018). The incidence rate of *Trueperella pyogenes*, responsible for summer mastitis in pastured cows, was found to be high during hot months and was linked to *Hydrrotaea irritans* (Rzewuska *et al.*, 2019).

Conclusions

HS has detrimental effects on the physiology, welfare, production, and reproduction of dairy cattle. It leads to reduced water intake and DMI, and increased body temperature, respiration rate, and panting, negatively impacting growth and production performance. HS alters the rumen environment, affecting blood composition, milk production, and composition. As a result, it decreases milk protein, but with unaffected lactose levels. Fertility in bulls and cows is significantly compromised, causing decreased conception rates, impaired embryonic development, higher embryonic mortality, and increased chances of twinning. Furthermore, HS increases the overall mortality rate. Therefore, it is imperative to implement effective measures to mitigate HS to enhance dairy cattle health, performance, and reproduction, thereby minimizing economic losses worldwide.

However, further studies are needed to determine the molecular basis for HS-mediated oxidative damage in mammary epithelial cells and to investigate how this affects milk protein synthesis. The specific inferences of rumen microbiota and their adaptive potential to HS are still unclear and need further investigation. Research into advanced mitigation strategies, including precision cooling technologies, diet strategies, and selection for metabolic stress tolerance traits, will be critical to developing sustainable options for controlling HS in dairy cows. Further understanding is needed regarding the long-term consequences of HS on reproductive physiology, particularly concerning embryonic development and follicular health.

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Table 2. Heat sensitive livestock diseases

Categories	Disease name	Causal agent	Transmission	Favorable weather condition	Clinical signs	Postmortem lesions	Prevention and control	Line of treatment	References
Viral diseases	Papillomatosis	Papillomavirus	-Contaminated fomites -Blood	More prevalent in hot summers	-Cauliflower growth on skin	-	-Avoid contact with infected animal	-Surgical removal -Autohemotherapy -Autogenous vaccine	(Read & Walker, 1998; Radostits *et al.*, 2006; Wilkie *et al.*, 2012; Abutarbush *et al.*, 2015; Angelos, 2015; Grace *et al.*, 2015; Morand, 2015; Walker & Klement, 2015; Aiello *et al.*, 2016; Bett *et al.*, 2017; Kimaro *et al.*, 2017; Akter *et al.*, 2020; Abed *et al.*, 2021; Bari *et al.*, 2022; Bulbul *et al.*, 2022)
	Lumpy skin disease	Neethling virus	-Stable flies -Mosquitoes -Hard ticks	More prevalent in hot summers	-Nodules throughout the skin and other parts of the body -Skin eruption	-	-Vaccination	-No specific treatment -Symptomatic therapy with high antihistaminic	
	Crimean- Congo hemorrhagic fever	Orthonairovirus	-Hard ticks (*Hyalomma spp.)* -Blood	Hot-humid conditions	-High fever -Muscle pains -Abdominal pain -Vomiting -Diarrhea	-	-Vaccination	-No specific treatment -Symptomatic therapy	
	Rift Valley Fever	Phlebovirus	-Direct or indirect transmission via blood or organs of infected animals -Mosquitoes (*Aedes, Culex spp.)*	Hot-humid conditions	-Fever -Vomiting -Diarrhea -Respiratory signs -Meningoencephalitis -Abortions	-Hepatic lesions -Severe lesions in aborted fetuses and newborn -Swollen spleen and peripheral lymph nodes	-Vaccination		
	Bluetongue	Orbivirus	-Insect-transmitted (*Culicoides midges*)	Hot-humid conditions	-High fever -Respiratory signs -Edema of lips, nose, face, submandibular area, and eyelids -Serous-mucopurulent nasal discharge -Frothy oral discharge	-Edema, congestion, and hemorrhages in the mouth, nose, nasal cavities, conjunctiva, coronary bands, and lungs -Inflammation, and necrosis in hoof coronets	-Vaccination -Insect control		
	Japanese encephalitis	Flavivirus	-Mosquito (*Culex spp.*)	Hot-humid conditions	-Fever -Neurological signs -Severe encephalitis -Reproductive losses (mummified and stillborn)	-Fetuses with no brains -Edematous testicles	- Destroy mosquito breeding sites -Vaccination		
	Bovine ephemeral fever	Rhabdovirus	-Arthropod-borne	Wet and summer	-Fever -Muscular stiffness -Shifting lameness	-Lesions in the lungs -Fibrin-rich fluid, or pinkish-blood-stained fluid in the heart sac, chest and abdominal cavities, and joint capsules -Edema and generalized hemorrhaging under the skin	-Vaccination	-Anti-inflammatory drugs -Other supportive treatments	

Categories	Disease name	Causal agent	Transmission	Favorable weather condition	Clinical signs	Postmortem lesions	Prevention and control	Line of treatment	References
Bacterial diseases	Infectious bovine keratoconjunctivitis	*Moraxella (M.) bovis, M. bovoculi, M. ovis, Mycoplasma (M.) bovis*, *M. bovoculi*	-Face flies -Fomites -Direct contact	More prevalent in hot summers	Ocular condition characterized by -Blepharospasm, -Conjunctivitis, -Lacrimation, -Corneal opacity	-Ulceration in or near the center of the cornea	-Control of flies - Good husbandry practices	-Antibiotic treatment -Supportive care	
	Mastitis	*Streptococcus spp.*, *Staphylococcus spp., E. coli, Klebsiella spp.* and other bacteria	-Milking machine -Contaminated hands and materials -Direct contact	Prevalent in all seasons	-Changes in milk -Change in udder -Systemic signs	-Swelling of udder	-Good husbandry practices -Avoid contamination		
	Anthrax	*Bacillus anthracis*	-Directly by spores	More prevalent in hot humid areas	-No specific signs -Sudden death -Respiratory or cardiac distress -Staggering	-Incomplete rigor mortis -Splenomegaly -Septicemia -Dark blood in the natural orifices (mouth, nostrils, and anus)	-Vaccination - Management of infected carcass	-Antibiotic treatment (penicillin) at early stage of infection	
	Leptospirosis	*Leptospira spp.*	-Direct contact with infected urine, placental fluids, or milk -Venereal or transplacental transmission -Poor management practices and environmental conditions -Rodents	Floods, wet season	-Renal or hepatic damage -Respiratory signs -Abortion -Stillbirth -Blood-tinged milk -Estrus repetition -Weak offspring	-Renal or hepatic lesions	-Vaccination -Proper management of environment	-Antibiotic treatment (ampicillin and oxytetracycline)	
	Foot rot	*Fusobacterium necrophorum, Prevotella levii*	-Wound or injury	Floods, wet season	-Swelling between claws of a hoof -Lameness	-Swollen, painful foot with necrosis -Foul-smell from inter-digital space	-Management of hooves	-Antibiotic treatment (procaine penicillin, ampicillin, and oxytetracycline)	
	Brucellosis	*Brucella spp. such as B. melitensis, B. abortus B. ovis, B. melitensis*	-Ingestion of *Brucella spp.* -Transmission via AI by contaminated semen	Hot-humid conditions	-Abortion -Stillborn -Weak calves -Retained placentas -Arthritis -Mastitis	-Ulcerative endometritis -Necrosis in cotyledon -Consolidation of lungs in fetus	-Vaccination	-No specific treatment -Symptomatic therapy -Carcass condemnation	
	Coxiellosis	*Coxiella burnetii*	-Tick-borne transmission - Transmission at parturition, via inhalation and ingestion	Hot-humid conditions	-Transient fever -Malaise -Profuse perspiration -Late abortion	-Endocarditis -Severe placentitis	-Vaccination -Abortion management -Environmental management	-Antibiotic treatment -Supportive care	

Categories	Disease name	Causal agent	Transmission	Favorable weather condition	Clinical signs	Postmortem lesions	Prevention and control	Line of treatment	References
			-Direct contact with birth fluids or placenta						
	Borreliosis	*Borrelia spp.*	-Tick-borne transmission, specially via *Ixodes*	Hot-humid conditions	-Fever -Stiffness -Swollen joints -Dropped milk yield	-Lymphadenopathy -Cutaneous lymphoma	-Vaccination -Control of ticks -Use of repellents and acaricides	Treatment with antibiotics such as beta-lactams and tetracycline -Symptomatic therapy	
	Dermatophilosis	*Dermatophilosis congolensis*	- Mechanical transmission via flies and ectoparasites -Direct contact	Hot-humid conditions	-Matted hairs -Greasy or creamy discharge -Hair loss with scabs -Cutaneous keratinized material	-Formation of pustules -Lesions in mouth, neck, leg, udder, back etc.	-Control of ectoparasites	-Topical treatment with chlorhexidine-based shampoo -Systemic antibiotics such as procaine penicillin	
	Contagious bovine pleuropneumonia	*Mycoplasma mycoides subsp mycoides*	-Inhaled infected droplets disseminated by coughing -Contact with sick animals	Dry season	-Fever up to 107°F -Painful and difficult breathing -Extended neck and open mouth breathing -Abducted elbow and arched back	-Pleural cavity with large quantities of yellowish-brown fluid along with pieces of fibrin -Thickening of pleura	-Vaccination -Restricted movement -Culling	-Antibiotics (tylosin tartrate) -Symptomatic therapy	
	Hemorrhagic septicemia	*Pasteurella multocida*	-Inhaled infected droplets disseminated by coughing	Rainy season	-Fever (106-107℉) -Edema in around throat, dewlaps, and brisket region -Respiratory distress	-Bronchopneumonia -Swollen lymph nodes	-Vaccination	Antibiotics (sulfonamides, tetracyclines, penicillin) at early stages	
Protozoal diseases	Ehrlichiosis	*Ehrlichia spp.*	-Tick-borne transmission	Hot-humid conditions	-Fever -Stiffness and reluctance to walk -Edema of limbs or scrotum -Coughing and dyspnea	-Splenomegaly -Reticuloendothelial hyperplasia -Lymphadenopathy	-Control of ticks -Use of repellents and acaricides	-Doxycycline -Tetracycline -Imidocarb diproprionate	
	Trypanosomiasis	*Trypanosoma spp. such as T congolense, T vivax, T brucei brucei, T simiae*	-Transmitted by tsetse fly	Hot-humid conditions	-Intermittent fever -Anemia -Blood in urine -Aching muscles	-Swollen lymph nodes and spleen	-Long term control of tsetse fly	-Treated with pentamidine or suramin (Stage I) -Treated with melarsop	
	Babesiosis	*Babesia spp.* such as *B. bovis, B. bigemina, B. divergens, B. major*	-Tick-borne transmission	Hot-humid conditions	-High fever -Hemoglobinemia -Hemoglobinuria -Brick red conjunctiva which soon changes to be paler -Severe anemia -Jaundice	-Swollen liver -Enlarge gallbladder containing thick granular bile -Swollen spleen and kidney	-Vaccination -Control of ticks -Use of acaricides	-Babesiacides such as diminazene aceturate, imidocarb di-propionate and oxytetracycline -Symptomatic treatment	

Categories	Disease name	Causal agent	Transmission	Favorable weather condition	Clinical signs	Postmortem lesions	Prevention and control	Line of treatment	References
	East Coast fever	*Theileria parva*	-Tick-borne transmission	Hot-humid conditions	-Fever (104-107°F): continuous or intermittent -Swollen superficial lymph nodes -Anemia followed by hemoglobinuria, jaundice, and prostration	-Enlargement of the liver, lymph nodes, and spleen -Pulmonary edema	-Vaccination -Control of ticks -Use of acaricides	-Use of parvaquone or buparvaquone -Symptomatic treatment followed by anti-inflammatory drugs and antidiuretics	
	Cowdriosis	*Ehrlichia ruminantium*	-Tick-borne transmission	Hot-humid conditions	-Fever -Edema in lungs -Congested and friable mucous membranes -Respiratory distress -Nervous signs -Hypovolemia	-Hydropericardium	-Vaccination -Long term control of ticks -Use of acaricides	-Use of oxytetracycline or doxycycline -Symptomatic treatment followed by corticosteroids and diazepam	
Reckitcheal diseases	Anaplasmosis	*Anaplasma spp.*	-Tick-borne transmission -Transplacental transmission	Hot-humid conditions	-Fever -Severe dyspnea -Anemia -Jaundice -Nervous signs -Muscle weakness and tremor	-Spleen is enlarged and soft with subcapsular hemorrhages -Mottled liver -Gallbladder is distended with thick brown or green bile	-Vaccination -Long term control of ticks -Use of acaricides	-Treatment with oxytetracycline and imidocarb di-propionate -Symptomatic treatment with antipyretic drug, hematinic drug, intravenous infusion, and sedative drugs	
Parasitic diseases	Haemonchosis	*Haemonchus contortus, Haemonchus placei*	-Horizontal transmission	Hot-humid conditions in sub-tropical regions	-Sub-mandibular edema -Diarrhea -Anemia -Rough hair coat -Death	-Ascites -Thickening of abomasal mucosa with hemorrhages and nodule development	-Vaccination	-Anthelmintics (albendazole, levamisole, and ivermectin) -Symptomatic treatment	
	Fasciolosis	*Fasciola hepatica*	-Aquatic snails	Floods, wet season, and presence of intermediate host	-Anemia -Submandibular edema	-Liver is enlarged and friable -Migratory tracts in liver	-Snail control -Pasture management	-Anthelmintics (Nitroxinil, triclabendazole and albendazole) -Symptomatic treatment	
	Schistosomiasis	*Schistosoma spp.*	-Direct contact	Dry season followed by wet season	-Diarrhea -Anemia -Snoring sounds during breathing	-Granulomas in the intestines and liver -Cauliflower-like growths on the nasal mucosa		Praziquantel	

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